Towards failure-based decision-making during design: user-centered design meets design methods research

Francesca A. Barrientos[*], Elin R. Pedersen[†], Irem Y. Tumer[*]

[*]Complex Systems Design Group
Intelligent Systems Division
NASA Ames Research Center
Moffett Field, CA, 94035, USA
francesca.a.barientos@nasa.gov
irem.y.tumer@nasa.gov

[†]Kraka, Inc.
Redwood City, CA, USA
elin@kraka.com

Abstract – *The Function Failure Design Method was introduced to enable failure-based decision-making during the early stages of conceptual design. In ongoing work, design researchers are validating this design method on NASA mission design data. To facilitate the adoption of this method by practicing design engineers, a user-centered design approach is applied to the development of the design method tools. This paper describes the multi-disciplinary approach used in this development effort which brings together user-centered design and design methodology research. The preliminary findings include descriptions of user work practice that should be supported by the decision-support tools. The goal of this work is to develop user interface prototype technologies to the level where they can be deployed in usability studies.*

Keywords: user-centered design, decision support, engineering design methods,

1 Introduction

Knowledge about the failure modes that disrupt functionality is critical to support engineers early in the design cycle in making design decisions that prevent or mitigate failures. Most failure identification methods are only effective at later design stages when detailed designs are available. To address this need, researchers at NASA Ames Research Center and the University of Missouri at Rolla have introduced the Function Failure Design Method (FFDM) [1][2][3]. Ongoing work concentrates on validating the method using design problems drawn from NASA mission design data.

The ultimate goal of any design theory and methodology research is to improve the design process in industry; however, relatively few research ideas advance to this stage. In a 2001 overview of the state of the art in function-based design research, Wood and Greer found that none of the methods they analyzed was in widespread use in industry [4]. Though the primary reason was immaturity of the design methods, they also suggest that the prescriptive design methods research process lacks a means to respond to the creative process needs of practicing design engineers as well as larger organizational, social and business needs.

This paper describes our efforts to bring the user perspective to design theory and methodology research and technology development. Specifically, we are designing the user interactions for a prototype software tool being developed to implement the FFDM. This tool, known as the Function Failure Design Tool (FFDt), provides a decision support resource for engineers to learn about potential failure modes that can affect a system they are designing. Our initial goal is to develop the user requirements for the tool and build user interface prototypes that can be assessed by potential users. In this paper we present our initial approach to assessing user needs and some of our preliminary findings.

Our target FFDt user is a mission design engineer who develops electro-mechanical space hardware. FFDt would be used during the conceptual stage of design, a stage characterized by incomplete and competing alternative solutions. Instead of relying on a failure analysis expert, the design engineer can use FFDt to selectively search a failure knowledge base for function specific failure modes.

2 Related work

2.1 Using Functional Models in early design

FFDM is based on the designer reasoning about a product at a functional level and developing a functional model that describes the main functions that meet the product's objectives [1][2][3]. These functions can be used to look up potential failure modes in a knowledge base of historical failure modes. By representing the design as abstract functions, FFDM enables engineers to relate failure mode information to the design before the design has been resolved into form specfic design solutions.

Usually, a particular function is described as a verb-object phrase, such as "import electrical energy." The vocabulary for these phrases is drawn from the *functional basis* [5], a standardized set of verbs for describing the action of a function and set of nouns for describing the flow that is acted upon.

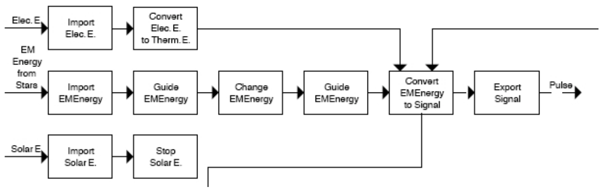

Figure 1. Detail of a functional model.

A design's functional model can be textually represented as a list all of the functions that a design must fulfill, or graphically represented as a diagram that describes how the functions and flows are interconnected. Figure 1 shows part of a functional model of an electrical design. Typically, the boxes are labeled with a function name (that is, the verb), and the links are labeled with a flow. In this paper, a *functional model* refers to this graphical representation.

2.2 User-centered design

The techniques we employed in gathing user data and developing usability requirements, particularly our use of scenarios and storyboards, are adapted from technques described in [6]. Some of our storyboards also employ elements of *rich pictures* as described in [7].

3 Approach

To develop insight into our target users and develop usability requirements, we have taken the following steps:

1. Gathered conceptual design user data
2. Studied functional modeling practices
3. Created detailed storyboards of plausible scenarios
4. Held critiquing session with design researchers

In this section we describe these steps and present preliminary findings.

3.1 Observing Conceptual design at NASA

During NASA's mission design process, explicit failure analysis occurs mainly during the later design phases when detailed designs are available. FFDt, on the other hand, is intended for use during early stage design. To understand the engineers' needs, we studied a conceptual design team at NASA's Jet Propulsion Laboratory(JPL). This team produces conceptual mission designs in order to assess feasibility and estimate preliminary cost. The study consisted of observing various design sessions and informally interviewing several team members. Though we do not necessarily intend to design FFDt specifically for this team, we use this data to provide baselines for understanding user needs.

One lesson we learned was that the engineers on this team are not always designing completely new functionality for each mission. More often, they are reusing components or selecting components that are similar to those that have been used on previous missions. Similarly, the engineers do not formulate new engineering models for every new mission design. Instead, they reuse models, often just lookup tables, from previous designs.

We also found that these engineers do not perform any explicit failure identification tasks during their design sessions. That is, there is no point when an engineer produces or looks up a list of failure modes that might affect their subsystem. It remains an open question whether engineers, in practice, find failure information useful for decision-making during conceptual design.

3.2 Functional modeler user data

To use FFDt, designers would be required to build and use functional models using the functional basis, so we studied the skills and knowledge necessary to create these models. To do this, we informally interviewed several design methods researchers who carry out research on function-based methods. In some sense, we treated these researchers as "proto-users." We guessed that these researchers would have developed personal practices for working with functional models, and that these personal practices might inform the design of FFDt.

We asked one of the functional modeling researchers to demonstrate the process of building functional models for both existing and clean sheet designs. This engineer usually creates the models on a computer using a general purpose drawing application. One of the observations we made was that he always started off by bringing out a copy of the functional basis glossary, and he referred to this glossary constantly while building the functional model. Note that this researcher is a very experienced functional modeler. When we asked other researchers about this practice, they confirmed that they always had glossaries of the functional basis close at hand, even as posters on the walls of their lab.

One of the questions we asked the researchers is whether they annotate their functional models, and, if so, how. All of the researchers responded that they used annotations. One researcher labeled the boxes in a functional model with the parts of the prduct being designed. For example, in a functional model for a hand-held can opener, he labeled the boxes that would be embodied as the handle of the can opener with the word "handle." Another type of annotation is drawing a polygon around portions of the functional model to show that they will be embodied in a single module.

We found this practice particularly interesting because an implicit tenet of function-based design is that functional models will encourage engineers to defer selecting the form of a design until a range of possible solutions is fully considered. Initially, we took this to mean that functional model representations should avoid references to form so as to avoid biasing the designer. However, these annotations appear to be useful in practice. Some of the annotations appear to serve as reminders of the relationship between portions of the functional model and physical parts of the product being designed. Annotations may also suggest design constraints. The “handle” label for the can opener annotation described above may serve as a reminder of the constraint that the can opener must permit itself to be grasped by a human. Further, the use of functional abstractions does not mean that candidate forms are not under consideration. Function and form are intimately related, and functions in a functional model can imply a generic class of embodiment. For instance, the function *convert electrical energy to rotational energy* implies the form of a motor, but the description is still generic; it does not specify exactly what type of motor to use.

We hypothesize that the user interaction design for FFDt must account for the engineer’s need to reason about the physical product being designed, even at the functional design stage. We believe that references to form will not necessarily hinder effective reasoning about functionality as long as the representations used remain abstract or preserve ambiguity. We draw this conclusion from other studies of the use of informal representations to reason about conceptual design. In [8], Goel suggests that informal sketches support creative design thinking because sketches are ambiguous symbols. In studies of the use of objects in conceptual design, Brereton and McGarry found that even hardware props support exploration of the design space because the functional meaning of the hardware changes with the design context [9].

3.3 User scenarios and UI storyboards

We then developed user scenarios and accompanying storyboards to capture our assumptions about the characteristics of likely FFDt users, our hypotheses about the ways in which FFDt would be used, and our ideas for tasks the user interface needs to support. To begin the process of developing scenarios, we created an example design problem drawn from an actual NASA mission design. The product being designed in our example is a star scanner, an instrument that uses starlight to calculate the orientation of a spacecraft. We created functional models for the star scanner and used these models to determine what failure modes would be found in the knowledge base. Then, given the models and these failure modes, we developed a list of the possible actions that an engineer might take upon seeing the failure information. The actions range from discarding irrelevant failure modes to considering design options to mitigate or prevent relevant failures. Among the design options we listed were:

- Add new functionality to the design that act as safeguards,
- Select particular component solutions that are not vulnerable to the failure modes,
- Modify the design to add redundant functionality.

This list of design options is hypothetical, but we can test its validity during user studies.

We elaborated upon the star tracker design example to build scenarios and storyboards. Here we present two of our scenarios. In the first scenario we assume that the engineer is proficient at creating and using functional models while in the second the engineer is a novice function modeler. For both scenarios we make a number of assumptions about the engineer who uses the tool:

- The engineer is not a failure modes expert.
- The engineer is an experienced mission design team member.
- The engineer is working on a conceptual design.

The engineer, in these scenarios, is responsible for designing the attitude control system (ACS) for a spacecraft and uses FFDt to search for potential failures in a knowledge base of historical failures.

<u>Scenario 1) Proficient functional modeler:</u> This experienced mission design team member creates functional models as part of her usual design process. She has designed many ACS’s in the past, so for this project, she retrieves a functional model from a previous design that she believes will be similar to this new design. She removes some of the detail from the functional model so that it matches the current partial solution she is working on. She decides that there are two critical functions that need to be protected, and she wants to learn about the failure modes that pertain to these functions. She invokes FFDt from the engineering modeling environment she is working in and inputs the critical functions. FFDt returns a dozen entries, and the engineer selects three of them as most relevant to the current product design. She decides that one of them can only be addressed through adding a shock absorber to the current design and begins to modify the functional model to reflect this decision.

<u>Scenario 2) Novice functional modeler:</u> The designer has concerns about protecting the integrity of critical modules in each subsystem, and one such module is the star scanner. In FFDt, the engineer browses through a directory of the different mission subsystems and retrieves a pre-defined functional model of the star scanner. The engineer first spends some time making sense of the model and relating it to the current design. Then she determines that *convert photoelectric energy* is the important function, especially since she is considering two different components to embody this function. She searches for the failure modes associated with this function, and a dozen failure modes are

returned. The engineer selects three of these failure modes as most relevant to the current design and the components under consideration. She notes that one of the failure modes will be mitigated by the redundant power source she has already included in the design, but that the other two might be a problem with another of the components she is considering.

There are several reasons for including a scenario in which the engineer is unfamiliar with functional modeling. First we wanted to explore the user interaction implications of designing a tool for a novice functional modeler who may have no skill or even desire to create their own functional models. This scenario explores the boundaries of how transparent we can make the functional modeling element of FFDt. One of the questions we are still trying to answer is is there a way to present the functional modeling information to the user without requiring the engineer to become proficient in functional modeling?

The proficient functional modeler scenario is more hypothetical since it describes a user who doesn't yet exist, a mission design engineer who uses functional modeling in their regular work practice. We use it to explore more technically advanced user interfaces such as using FFDt alongside an interactive visualization of a functional model, or alongside an interactive functional modeling editor.

After developing plausible scenarios, we began designing user interactions to support them. We created storyboards to document user interaction ideas, record design rationales and add detail to the developing scenarios. While adding details we were especially concerned with thinking through the particulars of the tool usage, including:

- What data does the engineer require in order to use the tool?
- What information must be made available to the user while the tool is in use?
- How often will the engineer use the tool, and what information will be saved between sessions?
- At the end of a session, how will the engineer use the information obtained?

3.4 Critique sessions

We involved the design methods researchers in our process by periodically presenting the scenarios and storyboards to them in critiquing sessions. (Figure 2 shows an example of the material presented during these sessions.) The researchers suggested new ideas for user interaction features or critiqued the plausibility of the scenarios. These sessions also allowed us to learn about the latest developments of the FFDM knowledge base data and related technology. As the knowledge base evolves, the user interface design needs to evolve with it. For instance, the increasing size of the knowledge base lead us to consider how aggregate or statistical information about the data in the knowledge base could be used to inform the user. A further benefit is that these sessions also provided us with an opportunity to learn more about the ideas and visions researchers had for how the FFDt could be used.

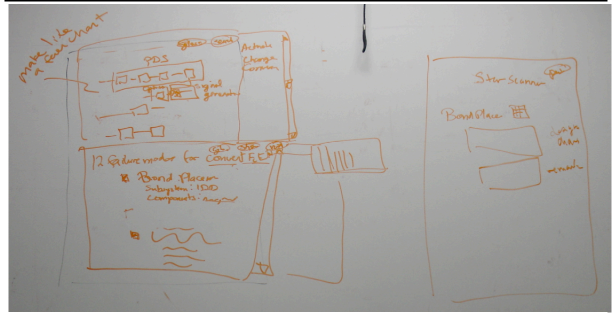

Figure 2. We presented storyboards of the user interaction to design methods researchers.

We believe that presenting the scenarios and storyboards to the design researchers may provide them with a new and useful perspective on FFDM development. Their main method for reasoning about and improving the FFDM is by applying it to specific design examples and analyzing the design outcomes. The user interface storyboards recontextualize the information provided by the knowledge base, showing only the information that would be presented to the user. This nudges the researchers to voice their opinions and concerns over the usefulness of the data to users rather than to the abstracted design process. In one of our critiquing sessions, one of the researchers said that the failure modes in the knowledge base may not be of interest at all to the conceptual design team that we described in Section 3.1 because the the inforamation is too specific for their needs.

4 Conceptual design of FFDt

FFDt itself passed through conceptual design phase. Our storyboards represent partial design solutions, and alternative solutions remain open and undecided upon. In the rest of this section we provide brief descriptions of the main features of the user interface but will not go into detail since the design is still tentative.

The user interface contains three main user interface objects that will be embodied as three panels: a) the functional model panel; b) the failure modes search results panel, and c) a glossary panel for the functional basis and the failure modes terms. The main purpose of the functional model panel is to allow the user to view and make sense of the model. Here we would allow users to make annotations to help them recall the relationship between the functional model and the physical design context. For example, in mission design the annotations might include the names of mission phases. The glossary panel is basically a scrolling text box, with a different pane for each glossary. The search results panel displays lists of failure modes in a hyperlinked text format.

The user performs a failure modes search by selecting functions from the functional model panel. Alternatively, the user can select functions using controls in the failure modes panel. (We believe this alternative is necessary to support users who do not want to work with the full function models.) After invoking the search function, failure modes appear in the failure modes panel.

The main activities supported by the search results panel is browsing and information seeking on failure modes. This panel may list dozens of failure modes, and we hypothesize that the user's main goal will be to determine the most relevant failure modes. The failure modes will be displayed alongside knowledge base information that we believe will help with this determination by providing the context in which the failures occurred. Users will, of course, use their own engineering judgement to decide if the failure modes are relevant. Because the usefulness of failure modes search is closely tied with the relevance of the data in the knowledge base, our likely development path is to prototype this panel in software and use this interactive prototype in user studies. Here we describe a possible embodiment of this panel.

The panel is divided into a controls area and the main display area. The controls area shows which functions are selected for search and has controls for adding and deleting functions. In the display area, functions are displayed in an alphabetically sorted list and their associated failure modes appear in an alphabetically sorted sublist. The failure mode information includes the name of the failure mode and summarized supporting information such as the subsystem and components in which the failure modes historically occurred and the frequency of the failure mode in the database. Hyperlinked text in the supporting information allows the user to drill down into the failure mode information in order to determine the relevance of the failure mode to the design.

5 Conclusions and future work

Decision support methodologies during engineering design provide prescriptive rules, guidelines or processes for engineers to follow in order to achieve a desired design outcome. Most methodologies are developed without consideration as to how they would be deployed in a real world design environment. In this paper we described our approach to designing a technology so that a novel engineering design methodology can be aligned with user needs and opportunities in an industrial setting.

We have described our approach to applying a user perspective to the development of FFDt, a tool to enable design engineers to use historical failure information during conceptual design. Our initial findings suggest that allowing users to annotate functional models with references to the design context may contribute to the tool's usability. We also hypothesize that users will need mission context data to determine the relevance to the failure data in the knowledge base.

Our approach is one way in which user centered design techniques can be used to inform the development of an engineering design methodology and its related technologies. The pilot user studies and scenario development approach described here are just preliminary steps in the larger project of identifying users who will find the FFDt useful for their work. We plan to develop the technologies for FFDt to the level where they can be deployed in user studies with practicing design engineers.

References

[1] I.Y. Tumer, R.B. Stone, Mapping Function to Failure During High-Risk Component Development. Journal of Research in Engineering Design. Vol. 14, pp. 25-33, 2003.

[2] R. B. Stone, I. Y. Tumer and M. Van Wie. "The Function Failure Design Method", *Journal of Mechanical Design*, in press, 2005.

[3] M.E.Stock, R.B. Stone, I. Y. Tumer, "Linking product function to historical failures to improve failure analysis in design" *Research in Engineering Design*, in press. 2005.

[4] K. Wood and J. Greer, "Function-Based Synthesis Methods in Engineering Design," *Formal Engineering Design Synthesis,* E. Antonsson and J. Cagan, eds. Cambridge University Press, New York, pp.170-227, 2001.

[5] J. Hirtz, R. Stone, D. McAdams, S. Szykman and K. Wood, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts", *Research in Engineering Design,* Vol. 13 No. 2, pp. 65-82, 2002.

[6] H. Beyer and K. Holtzblatt, *Contextual Design: A Customer-Centered Approach to Systems Designs*, Morgan Kaufman, San Francisco, California. 1997.

[7] A. Monk and S. Howard, "The rich picture: a tool for reasoning about work context," *interactions*, Vol. 5, No. 2, pp. 21-30, 1998.

[8] V. Goel, Cognitive role of ill-structured representations in preliminary design," in *Proceedings of Visual and Spatial Reasoning in Design,* MIT, Cambridge MA, pp 131-145, 1999.

[9] M. Brereton and B. McGarry, "An observational study of how objects support engineering design thinking and communication: implications for the design of tangible media", *Proceedings SIGCHI Conference on Human factors in Computing Systems,* The Hague, The Netherlands, pp. 217-224, 2000.